THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Variation management for cost-efficient integration of variable renewable electricity

VIKTOR WALTER

Department of Space, Earth and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2020

Variation management for cost-efficient integration of variable renewable electricity

VIKTOR WALTER

Department of Space, Earth and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden

Printed by Chalmers Reproservice
Gothenburg, Sweden 2020

Variation management for cost-efficient integration of variable renewable electricity

VIKTOR WALTER

Department of Space, Earth and Environment

Chalmers University of Technology

Abstract

The aim of this work is to improve our understanding of how wind power and solar photovoltaics (PV) can be integrated into the electricity system in a cost-efficient manner. For this, a techno-economic cost-minimising model of the electricity system is used for a set of case studies. The case studies cover a set of regions that have different conditions for wind and solar power and employ a range of strategies for variation management. The variation management includes the availability of complementing, shifting, and absorbing strategies internal to the electricity system, such as flexible bio-based generation, batteries, and transmission, as well as measures available from electrification of the industry, transportation, and heating sectors.

The results show that there is a need for different variation management strategies in different system contexts. In regions with exceptionally good conditions for variable renewable electricity (VRE), wind and solar power integration benefits from absorbing strategies. In regions where the conditions for VRE are not sufficient to out-compete baseload generation, complementing technologies are needed to enable cost-efficient wind and solar power integration. Shifting strategies are primarily suited to the diurnal variations of solar PV. Variation management can increase the amount of cost-efficient VRE that can be integrated into the system while reducing the total cost of meeting the demand for electricity. The most valuable variation management strategy covered in this work involves optimising charging of electric vehicles and vehicle-to-grid (discharging from electric cars to the grid), which can reduce the total cost by up to 33% in a solar-dominated system but by only 8% in a wind power- and hydropower-rich region with inherent flexibility. The value of transmission lies in its abilities to smoothen wind variations between regions and to transfer electricity from electricity systems with superior wind or solar power resources. A scarcity of bioenergy would entail a high value being placed on available biomass for the purpose of complementing wind and solar power. To maximise the provision of flexibility by biomass, it could be utilised with negative emission technologies to enable the usage of fossil-derived natural gas. Biomass deployed to meet net-negative emissions targets would, however, not provide flexibility. The results of this work underline the importance of combining different technologies and strategies and the value of using them where they are best suited rather than deploying one strategy to resolve every situation.

Keywords: Energy system modelling, flexibility measures, smart energy systems, variable renewable electricity, variation management strategies

Acknowledgements

I would like to thank my supervisors Filip Johnsson and Lisa Göransson for the opportunity to pursue my PhD with your support. Thank you, Lisa, for pushing me and supporting my work in all kinds of ways. Also, for all discussions about future topics and the guidance in how to progress with the plans.

Collaborators, thank you for good teamwork and the joy of not working alone. I also want to thank Ludwig Thorson for some great years of office sharing with the daily discussions about everything.

I would like to thank everyone in the group for interesting discussions in both formal and informal meetings. Also, thanks to everyone at the division for making Energy technology a nice working place.

Finally, I would like to thank my family and especially my wife Caroline for all your love and support.

Viktor Walter
Ljungskile, September 2020

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. V. Johansson and L. Göransson (2019). “Impact of variation management on cost-optimal investments in wind power and solar photovoltaics”. *Renewable Energy Focus* **32**, pp. 10-22. DOI: 10.1016/j.ref.2019.10.003

II. V. Johansson, M. Lehtveer and L. Göransson (2018). “Biomass in the electricity system - A complement to variable renewables or a source of negative emissions?”. *Energy* **168**, pp. 532-541. DOI: 10.1016/j.energy.2018.11.112

III. M. Taljegard, V. Walter, L. Göransson, M. Odenberger and F. Johnsson (2019). “Impact of electric vehicles on the cost-competitiveness of generation and storage technologies in the electricity system”. *Environmental Research Letters* **14**. DOI: 10.1088/1748-9326/ab5e6b

IV. V. Walter and L. Göransson (to be submitted). “Transmission as a variation management strategy”. To be submitted to *Smart Energy*.

Viktor Walter (previously Johansson) is the principal author of **Papers I**, **II** and **IV**, and conducted most of the modelling and calculations for these papers. **Paper III** is the result of joint work with Maria Taljegård, where the author contributed with analysis, discussion and editing. Lisa Göransson contributed with modelling and analysis of **Paper I** and with discussion and editing of all the papers. Mariliis Lehtveer contributed with analysis, writing, discussion and editing of **Paper II**. Mikael Odenberger and Filip Johnsson contributed with discussion and editing of **Paper III**.

Other publications

Other publications by the author, not included in the thesis:

A. V. Johansson, L. Thorson, J. Goop, L. Göransson, M. Odenberger, L. Reichenberg, M. Taljegard and F. Johnsson (2017). "Value of wind power – Implications from specific power". *Energy* **126**, pp. 352-360. DOI: 10.1016/j.energy.2017.03.038

B. V. Johansson, L. Thorson and L. Göransson (2017). "A quantitative method for evaluation of variation management strategies for integration of renewable electricity". *Proceedings of the 16th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants*. Berlin, Germany.

C. L. Göransson, M. Lehtveer, E. Nyholm, M. Taljegard and V. Walter (2019). "The Benefit of Collaboration in the North European Electricity System Transition—System and Sector Perspectives". *Energies* **12**. DOI: 10.3390/en12244648

D. P. Holmér, J. Ullmark, L. Göransson, V. Walter and F. Johnsson (2020). "Impacts of thermal energy storage on the management of variable demand and production in electricity and district heating systems: a Swedish case study". *International Journal of Sustainable Energy* **39**, pp. 446-464. DOI: 10.1080/14786451.2020.1716757

Table of Content

1 Introduction

Global responses to climate change, setting the goal of restricting global warming to well below 2°C above pre-industrial levels, were agreed upon in Paris in 2015 [1]. To meet this target, rapid decarbonisation of all energy sectors is needed, together with large-scale deployment of negative-emissions technologies [2]. Transformation to a carbon-neutral electricity system, together with electrification of other sectors are identified as key enablers in tackling this challenge [3]. The electricity sector can be decarbonised through a mix of renewable sources, carbon capture and storage (CCS), and nuclear power. Each of these solutions is to some extent connected to economic, social and technological challenges. Wind power and solar photovoltaics (PV) are promising technologies due to their low costs and high technical potentials. Utilising weather-based resources does not result in any direct CO_2 emissions, and the life-cycle emissions are low. However, given that the electricity generated by wind power and solar PV is dependent upon the weather, it provides variable renewable electricity (VRE). Due to weather variations occurring on different timescales, the generation becomes irregular, resulting in difficulties in meeting the demand and utilising the VRE. Balancing variable generation and demand is regarded as one of the main challenges associated with achieving high shares of VRE in the electricity system [4]. This thesis focuses on how to handle the variability of electricity generation and investigates the optimal way to integrate wind and solar power into the electricity system in a cost-efficient manner.

In managing the variability of wind power and solar PV, having access to flexible electricity generation technologies is beneficial. The most-flexible, fuel-based technologies are currently gas turbines, which can be fuelled with methane from fossil (natural gas) or biogenic (biogas) sources. However, the supply of sustainable biomass is highly uncertain, as are the means to distribute it across sectors and between applications, since there will be a need for renewable fuels in all sectors and most likely a need for negative emissions [5][6]. Another important source of flexibility is sectoral coupling of, for example, the transport sector with the electricity system. Large-scale integration of electric vehicles into the electricity system increases the electricity demand, and if charged directly when parked these vehicles could increase the variability of the load. Smart charging and the discharging of cars back to the grid (vehicle-to-grid, V2G) can be important for flexibility provision [7]. In addition, geographical variations in weather patterns can be used to smoothen variations in weather-based generation [8]. Trading of electricity can not only confer flexibility, but also enable the transfer of VRE resources between regions that have different conditions for the expansion of VRE. Combining different sources of flexibility and expanding the system from the traditional electricity system to other sectors are of importance for the large-scale integration of wind and solar power [9].

The issues and opportunities related to VRE integration can be investigated in energy system optimisation models. This renders the possibility to test how the conditions in various regions, with different weather conditions, can cope with the integration without having to test it in the real world. Energy system modelling can, therefore, reveal how different constraints affect the energy transition and identify areas that are more or less important and in need of policies or actions to achieve the transition. Cost-efficient integration of variable renewables is a multi-dimensional optimisation problem that requires specific tools to obtain clarity and reduce concerns related to the insecurity of high shares of VRE in the electricity system. Here, energy system modelling is used to improve our understanding of how supply and demand can be balanced by means of variation management strategies in different scenarios and different contexts of the future electricity system.

1.1 Aim and scope

This thesis focuses on elucidating: (i) how supply and demand can be balanced in electricity systems with high shares of wind and solar power; (ii) how increased flexibility can facilitate more VRE; and (iii) the value of different kinds of flexibility. These questions are addressed in the appended papers, which describe case studies directed towards the following questions:

- How will different variation management technologies, applied either separately or in combination, affect the cost-optimal system composition of the electricity system?
- With regard to filling the current knowledge gap on bioenergy in the electricity system:
    - What is the value of bioenergy in the electricity system?
    - Which biomass-based technologies should be part of the least-cost electricity system composition under various biomass supply conditions and different emissions targets?
    - Under which conditions do biomass-based technologies and variable renewables act as complementary factors or competitors within the electricity system?
- How do electric vehicles influence the cost-competitiveness of generation and storage technologies in the electricity system?
- What are the impacts of different transmission features, i.e., as enablers of VRE resource transfer from remote areas and for geographical smoothing, on the integration of VRE, in relation to other variation management strategies?

In **Paper II**, three European regions, Hungary, Ireland, and central Spain, are modelled to capture the different conditions for generation from wind and solar power. Central Sweden (the Stockholm price area) is included in the group of regions for **Papers I** and **III**, to capture interactions with hydropower. Two base regions, Hungary and Ireland, are connected to other European regions with similar annual electricity demands in **Paper IV**, to address the roles of transmission. **Paper I** considers a potential electricity demand for industrial hydrogen, the opportunity to sell heat from electricity for district heating purposes, and the possibility to move in time part of the household demand for electricity. In **Paper II**, the supply of biomass, biomass conversion technologies, and the carbon emissions limit are subjected to analysis. Electrification of light vehicles is included in **Paper III**. The temporal scope is a future year around Year 2050, modelled with a chronological one-hourly resolution in **Papers I** and **III** and three-hourly resolution in **Papers II** and **IV**.

1.2 Contribution of this thesis

Strategies for balancing the electricity system on an hourly basis within one year are in this work referred to as variation management strategies (VMS), which are categorised into absorbing, complementing, and shifting strategies, on the basis of economics and functionality

[10]. This work contributes to understanding the roles of flexibility measures, such as electricity storage and electrification strategies, applied separately or in combinations. **Paper I** covers several of the strategies, so as to capture the impacts from the three VMS categories. Based on the results shown in **Paper I**, the categories proposed previously [10] are refined to capture the functionalities of the VMS, revealing ways to handle frequent variations (shifting) or durable high (complementing) and low (absorbing) net-load events (see the VMS triangle [11] in Figure 1). The geographical scope is chosen so as to address the different possibilities for generation from VRE and to capture the need for variation management in regions with different VRE resources. In **Papers II–IV**, more-specific variation strategies are addressed, and the VMS triangle is further explored.

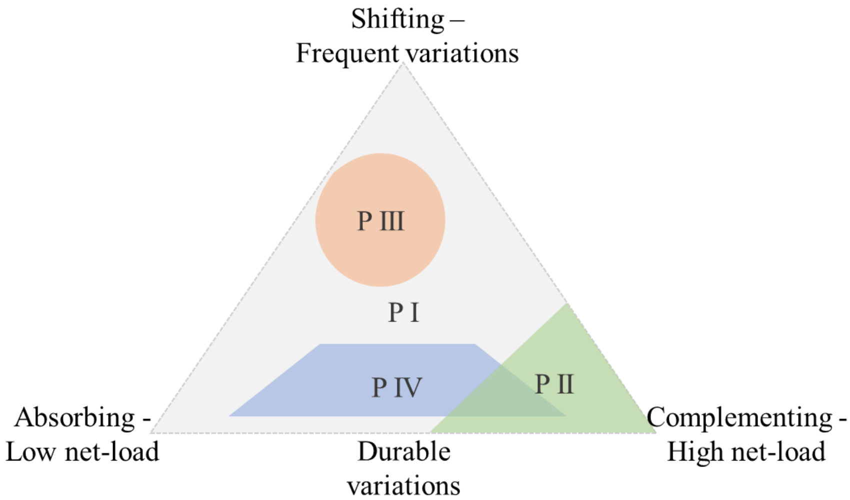

Figure 1: The variation management triangle and the parts of it explored in each of the appended Papers.

2 Background and related work

Historically, the electricity demand has been the source of variation in the electricity system, with one or two daily peaks and seasonal variations in some countries related to increased usage of electric heating during cold periods of the year. As a response to these variations, base-, intermediate-, and peak-load technologies have been applied [12]. Baseload technologies typically have a high investment cost and low running cost and run at full capacity for most of the year. In contrast, peak-load technologies are expensive to run and have a comparatively low investment cost; they only run for a few hundred or thousand hours and are fast-ramping. Intermediate-load technologies cover the interval between baseload and peak-load technologies. The merit order in terms of load-handling technologies for use in the system is based on the variable cost to generate electricity from the different technologies.

Since wind and solar power generation technologies incur no or low variable costs, they are placed early in the merit order, and the load variations are joined by the variations in supply. By subtracting the VRE generation from the load, the net-load is calculated. As the levels of wind and solar power increase in the electricity system, the variations in net load go from being dependent upon the demand to being more characterised by the weather-based generation patterns. In systems that are supplied to a large extent by VRE, high-load hours with no or low-level generation from VRE are *high-net-load hours*, and hours during which a large share of the load is covered by VRE are *low-net-load hours*. There are several alternatives for maintaining the balance between electricity supply and demand, ranging from conventional flexible generation technologies, energy storage units, and trade to demand-side options to control current demand as well as using electricity for new purposes in other sectors [13]. The timeframe over which the multitude of flexibility strategies maintains the balance ranges from milliseconds to several months.

2.1 Flexibility and high share of VRE in energy system models

Extensive electricity system optimisation modelling that includes different VMS has been carried out in recent years [14]. These studies have covered topics from flexible generation and storages to transmission and smart electrification. There are thermal generation technologies that can serve as baseload, intermediate-load, and peak-load technologies that fit well with the historical load variations. At a low level of VRE, the electricity system mainly comprises baseload, which is totally phased out at about 50% VRE, after which the need for more flexible peak load generation is the dominating thermal source of electricity [15]. To address the choice of thermal units and also the potential flexibility of, especially, intermediate-load generation, it is important to represent the cycling properties of these thermal units [16]. The properties are to some extent a question of cost, as plants could be designed to be more flexible. However, as the addition of cost also increases the need for utilisation to bring in revenue, improving technical flexibility reduces economic flexibility, although it could still be of value in terms of additional VRE integration [17]. Providing scope for wind power and solar PV generation by reducing the electricity production to the minimum compliant load in the thermal baseload or intermediate-load generation units is an absorbing strategy for integration of VRE into electricity systems that are dominated by thermal generation. Flexible peak-generation technologies complement VRE during high-net-load events. Hydropower can be operated so as to integrate wind power similarly to flexible thermal generation, which increases the value of VRE [18]. In this thesis, hydropower refers to reservoir hydropower, where the water can be stored and subsequently dispatched.

As an alternative to absorbing the generation peaks from VRE, some of the generation can be curtailed, resulting in a negative net-load and zero price for electricity (planned curtailment may have a value with respect to up-regulation in reserve markets) [19]. The wind turbines can also be designed to produce electricity in a more system-friendly way, through reaching the maximum output earlier and then curtailing more of the wind energy before it is converted to electricity [20]–[22]. This allows more wind power to be installed before reducing its own value. That would, however, increase the investment cost and result in a lower capacity density, which means that more land would be required for the same annual level of generation from wind power.

Another technology that is strongly linked to VRE integration is batteries. Smoothing the electricity generation from VRE in time provides the possibility to utilise weather-based electricity with a higher degree of freedom. Low-cost battery storage has been shown to allow solar PV to become the major source of electricity in the US, in competition with fossil fuels and without policy intervention [23] Reichenberg et al. [24] have demonstrated how wind and solar power, together with transmission and batteries are efficient at achieving system integration levels of 85%–98% VRE, highlighting the difficulty associated with covering the remaining fraction in the absence of flexible generation technologies. At high levels of VRE, wind power accompanied by transmission expansion competes with solar PV accompanied by batteries [24], [25]. Wind power benefits from geographical smoothing at different distance and temporal scales due to the movement of weather patterns [26]. Transmission has also been investigated in combination with household Demand-Side Management (DSM) in a dispatch model, in which it is shown to reduce the need for peak generation [27]. The time period for which electricity consumption in households can be delayed is, however, expected to be too short to have a significant impact on durable wind variations.

Electrification of other energy sectors or sectoral coupling with the electricity system refers to expansion of the electricity system so as to cover parts of the energy demands for heating, transportation, and industries. These sectors are especially interesting due to the low-cost storage systems for other energy carriers, such as hot water for heating or hydrogen for industry. The need for batteries as the energy carrier in the transportation sector makes battery charging a potential source of flexibility. Studies on electric heating show that a district heating system can benefit from wind power integration by switching between generating electricity together with heat in combined heat and power plants and consuming electricity for heat generation in electric boilers and heat pumps [28]–[30]. This gives the possibility to absorb low-cost electricity at low net-load events. When used in combinations with heat storage the impacts are larger than if the heat is required to match the demand directly. Electricity can also drive the process for direct air capture of carbon dioxide for negative emissions purposes or to fuel electrolysis to produce hydrogen for industrial needs. A comparison of the industrial usage of hydrogen and its use for electricity storage with subsequent conversion back to hydrogen through fuel cells reveals that the industrial usage yields greater savings, since excluding fuel cells saves in terms of both cost and efficiency losses [31]. The direct air capture process could be run on otherwise curtailed electricity, assuming that this would be economical even when including investment costs in the modelling [32]. Most of the electricity system costs for covering the demand for electrified transportation can be saved by smart charging of the electric vehicles rather than charging the vehicles directly when parked [33]. These results hold true also when including driving behaviours from GPS (global positioning system) data [34].

Combinations and comparisons of different strategies show that electrification strategies are more important than short-term storage options in the wind-dominated northern European context [35], [36]. Recent studies have shown the electricity system benefits derived from VMS, which are combined in a more holistic perspective (including several of the sectors, regions and storage alternatives) of the energy system with the focus on the electricity side [37], [38].

3 Method

Throughout this project (**Papers I–IV**), the same model, ENODE, has been used to address questions regarding technologies, strategies and sectors that provide variation management to the electricity system. Within the work, features have been added to the model, which in some cases have become standard, while in other cases they are only used in specific papers. The work is carried out in the form of case studies that capture the interactions between technologies in the electricity system for different system contexts, as summarised in Table 1. In **Paper I**, several VMS were included separately or in combination. In **Paper 2**, the supply of biomass was addressed as the ratio (in the range of 0–1) of the primary energy in the biomass to the annual electricity demand. Within this study, two other parameters are varied: 1) the target of either net-zero emissions or negative emissions (100% or 110% less than the electricity system emissions in Year 1990); and 2) whether or not CCS technologies are allowed. In **Paper III**, where the role of electric vehicles was investigated, the battery sizes, charging strategy, share of participants, and charging infrastructure were varied between the cases. In **Paper IV**, the trading regions, transmission costs, and the wind profile differences (whether or not the regions had synchronised profiles, with either a stable or unstable profile) were varied to assess the importance levels of two different transmission features.

Table 1: Summary of the studies described in the appended papers, including the modelling dimensions.

	PAPER I	**PAPER II**	**PAPER III**	**PAPER IV**
UNDER INVESTIGATION	Several VMS* separately or combined	Efficient usage of biomass; Negative emissions	Charging strategies for electric vehicles	Transmission features – Geographic smoothing and resource transfer
TIME	Hourly for 1 year	3-hourly for 1 year	Hourly for 1 year	3-hourly for 1 year
GEOGRAPHICAL REGIONS	Central Spain, Hungary, Ireland, central Sweden	Central Spain, Hungary, Ireland	Central Spain, Hungary, Ireland, central Sweden	Hungary, Ireland, (western Germany, eastern France, southern Poland, Romania)
SECTORS	Electricity, Heating, Industry	Electricity	Electricity, Transportation	Electricity
SPECIFIC TECHNOLOGIES	Batteries, DSM**, Electrolysis and Hydrogen storage, Electric boilers	BECCS***, Gasification, Fuel cells	Electric vehicles	Transmission

* VMS, Variation management strategies
** DSM, Demand-side management
*** BECCS, Bioenergy with carbon capture and storage

3.1 The ENODE model

ENODE (wordplay on the original in-house name in Swedish and English) is a linear optimisation model that is written in GAMS. It was first presented in the paper of Göransson et al. [16], wherein it was designed to capture the interplay between VRE and thermal generation technologies. Subsequently, it has been used to address variation management in more than a handful of projects. The model minimises the total cost of annualised investments and dispatch for a Greenfield electricity system with net-zero carbon emissions for one future year, with perfect foresight. In the electricity system modelling, importance is attached to the resolution of different dimensions, including time, space, technologies and boundaries to other parts of the energy system, such as the electrification of other sectors.

3.1.1 Time

The temporal dimension can relate to the number of time-steps within 1 year and to whether the time-steps are consecutive or separate. The choice of temporal scope also includes the choice as to whether the time starts from now and steps forward in time or jumps to a future Greenfield year with suitable assumptions being made as to costs and policies, such as carbon emissions constraints. In the case of ENODE, time is modelled as a single Greenfield year with hourly or three-hourly resolution with full chronology within the year. The chronology enables variation management to work on timescales that range from hours up to 1 year, to match the historical load and generation levels with weather patterns for the same year. Using the load, wind power, and solar PV generation profiles for the same years allows one to couple the relationships between parameters that would otherwise be difficult to estimate. These include correlations between generation from wind and solar and the temperature for heating demand as well as the ability to capture the lengths of high- and low-generation periods. The potential lock-in to the current power plant fleet, as well as the transition pathway are lost in the Greenfield approach. Nevertheless, the studies included here are focused on the dynamics between generation technologies and VMS in a future, carbon-neutral electricity system, for which purpose the Greenfield approach is deemed suitable.

3.1.2 Space

In **Papers I–III**, single copper-plate regions in the size of electricity price areas are modelled in isolation. This enables perfect geographical smoothing of weather variations within the available areas in the region, although it eliminates the potential benefits from trading electricity with other regions *via* existing or new transmission lines. Thus, the short-term variability within the region is under-estimated and the variability on a timescale of several hours as well as the need for self-sufficiency are exaggerated. Transmission between region-pairs is modelled in **Paper IV** as net transfer capacity optimised together with the generation and storage options. Transmission is under-represented also in **Paper IV**, although single regions, as well as region-pairs allow capture of the impacts on specific systems that are suited to wind power and/or solar PV with different underlying potentials for variation management. In **Paper IV**, four investment cost levels of transmission are modelled without taking distance into account, i.e., 10 (isolation), 3, 1 and 0 M€/MW (for free), so as to capture the value and role of transmission. The wind profiles were altered to understand better the role of transmission. A case with the original profiles was compared to cases with synchronised profiles in both regions, to address the value of resource transfer between regions with different resource availabilities in isolation from the value of geographical smoothing.

3.1.3 Technologies and boundaries

The technologies used include conventional and new generation technologies, storage systems, and methods for including the electricity demands from other sectors. Biomass, biogas, coal and natural gas plants (open and closed cycle gas turbine plants) with and without CCS, as well as nuclear power plants are the basic dispatchable options in the modelling [16]. CCS refers to a carbon-neutral mix of coal/natural gas co-fired with biomass/biogas in **Papers I**, **III** and **IV** and negative emissions from bio-CCS (BECCS) in **Paper II**. Thermal plants are associated with investment costs, variable and fixed operations and maintenance costs, fuel costs, carbon dioxide emissions from the fuel, and cycling costs and emissions from start-ups and part-load [39]–[41]. Biomass is assumed to be sustainable and simplified to be carbon-neutral. The investment costs in electricity generation and storages are annualised with a discount rate of 5% and with the technical lifetimes used as economic lifetimes.

The wind power, solar PV, and load profiles are representative of Year 2012, and a summary of the resources and demands is shown in Table 2. The wind power production is modelled as wind farms with re-analysis data, divided into 12 classes [21],[42]–[45]. Solar PV is modelled as mono-crystalline silicon cells installed at a fixed optimal tilt with one generation profile for each region [42],[46]. Hydropower is modelled for the region of central Sweden, representing the locally generated hydropower and the hydropower imported from northern Sweden (with historical limits on ramp-rates in **Paper I**) [47], [48]. The economic data for wind power and solar PV have been updated during the work and stem from the reports [39], [49], [50]. Economic and technical data for variation management technologies were acquired from the Danish Energy Agency [50].

The load was modelled as the historical demand [51]. In **Paper I**, the possibility to shift 20% of the load for up to 12 hours was included as household DSM (without linking any costs to this) [27], [52]. While it might be more accurate to apply a dynamic share of the load according to the need for heating during different periods, highly detailed models would be needed to capture the non-linearities in the cooling and warming processes of buildings. In **Paper I**, electric boilers were modelled as potential electricity consumers for supplying the demand for district heating [53]. The income from heat sales was included as a simplification based on the modelled price for district heating in Gothenburg [54], [55].

Lithium-ion and Vanadium redox flow batteries were modelled in **Paper I** with fixed C-rates (the ratio between the storage and charging potential; a C-rate of 0.5 or 0.25 describes storage systems that can be fully charged in 2 or 4 hours, respectively). The batteries in **Papers II–IV** were divided into separate investments in storage and charge/discharge capacities, representing only Lithium-ion batteries. This separation was useful, as a portion of the battery cost was assigned to the charging capacity, after which the models started to design batteries with lower C-rates (i.e., longer endurance).

The industrial hydrogen demand was modelled in **Paper I**, whereby hydrogen had to be produced by electrolysis. The demand for hydrogen was modelled as an additional need for 20% energy as hydrogen, spread evenly over the year, including conversion losses for the production and storage of hydrogen. The possibility to over-produce and store hydrogen in underground rock caverns for long-term storage with tanks so as to cope with small fluctuations in demand was evaluated in this work. In **Papers II–IV**, the possibilities to invest in electrolysis, underground storage, and (in addition to earlier work) fuel cells for generating electricity from the stored hydrogen are included, although without an exogenous demand for hydrogen for the industry.

In **Paper III**, the transportation sector was modelled as 426 individual cars with individual driving patterns based on Swedish GPS driving data, up-scaled to 60% of today’s car fleet [56]. Charging of the batteries was modelled either as direct charging, optimised charging or the opportunity to discharge the batteries back to the grid (V2G), with the driving demand being met to the same degree in all cases. Three different battery sizes were used: small, 15 kWh; medium, 30 kWh; and large, 85 kWh. Not included was the cost of the batteries, as the size is dimensioned for the purpose of driving rather than for the purpose of the grid. Infrastructural questions were taken into account by allowing charging at 7 kW at: all stops, stops longer than 6 hours or only at the home location.

All fuels are included exogenously, with the exception of biogas, which is assumed to be produced through the gasification of solid biomass. In **Papers I**, **III** and **IV**, the cost of biogas is connected to the biomass prices based on a 70% conversion efficiency and an added cost of 20 €/MWh_{th} for the gasification plant [57]. In **Paper III**, the amount of biomass is limited, and the fuel is supplied for free and with the marginal value set by the limit to the supply. A more detailed description of gasification is included to capture the possibilities for enhancing biogas production by adding hydrogen and electricity to the process [58]. Potentially conservative assumptions regarding the additional methanation process when combining carbon dioxide and hydrogen make this representation rather similar to the simpler version used in the other papers.

Table 2: Full-load hours (FLH) and maximum capacity (Cap) limits for onshore wind classes 1–12, offshore wind, solar PV, hydropower and the electricity demand.

Wind class and technology	**Central Spain**		**Hungary**		**Ireland**		**Central Sweden**	
	FLH [h]	Cap [GW]	FLH [h]	Cap [GW]	FLH [h]	Cap [GW]	FLH [h]	Cap [GW]
1	960	0.4	1,190	0.0	-	-	-	-
2	1,550	3.6	1,670	1.3	-	-	-	-
3	2,020	12.0	2,100	5.5	-	-	2,030	0.6
4	2,310	7.1	2,370	7.8	-	-	2,230	4.5
5	2,560	6.1	2,570	2.4	-	-	2,440	6.9
6	2,790	6.3	2,750	1.3	-	-	2,620	9.9
7	3,020	4.6	3,070	2.4	-	-	2,900	9.1
8	3,300	1.3	3,350	0.2	-	-	3,270	11.6
9	-	-	-	-	-	-	3,700	1.5
10	-	-	-	-	4,240	0.3	4,120	1.7
11	-	-	-	-	4,640	13.8	4,600	0.5
12	-	-	-	-	5,360	2.1	5,260	0.1
Offshore	-	-	-	-	5,360	…	5,260	…
Solar PV	1,770	…	1,360	…	1,000	…	1,050	…
Hydropower	-	-	-	-	-	-	3,750	9.6
Demand	5,310	15.1	6,030	6.5	5,010	5.7	4,800	18.6

4 Main results

4.1 Resource- and system-related limitations to VRE integration

The amount of VRE that can be cost-efficiently integrated into the electricity system is subject to two main limitations: (i) the remaining sites for VRE generation have poor conditions for VRE generation and VRE is out-competed by baseload generation; or (ii) additional VRE generation is extensively curtailed and VRE out-competes itself. The concepts of resource-limited and system-limited VRE (defined in **Paper I**) refer to the first and second conditions, respectively. It has been found that the choice of VMS to increase the cost-optimal share of VRE in an electricity system depends on which of these two limitations is active. At a low penetration level, the system value of installing wind power is high, as compared to the costs it has to cover. However, the marginal value of additional investments is reduced as the penetration level increases, as shown in Figure 2. The first reduction occurs as the choice gradually tends towards worse wind classes, together with slowly increasing costs for integration. In this phase, with wind power supplying 0%–60% of the annual demand for electricity, the wind power together with some complementing generation replace the baseload technologies. If the cost-optimal share of wind power is reached before the baseload is phased out it is resource-limited. Cheaper complementing generation could, at that level, support the marginal value of wind power to supply a larger share of the generation mix. Resource-limited generation does not mean that all areas are used, but that the areas that remain are un-economical without support. At a high penetration level, i.e., when wind power supplies more than 60% of the annual electricity demand, additional investments lead to increased curtailment and, therefore, have weaker impacts on the residual system. If the cost-optimal share of wind power is high, it is system-limited. At this stage, expanding wind power through an absorbing VMS from system expansion has the greatest effect.

The marginal system value of solar PV is high when there are low levels of solar PV in the system, since it reduces the need for peak generation during the middle hours of the day. On its own, however, solar PV quickly becomes system-limited, as the generation is strongly concentrated. The cost-optimal share of system-limited solar PV is efficiently increased by introducing shifting VMS, such as the usage of batteries. Additional integration of system-limited combinations of solar PV and shifting strategies benefit from durable complementing and absorbing strategies to manage cloudy days or seasonal variations.

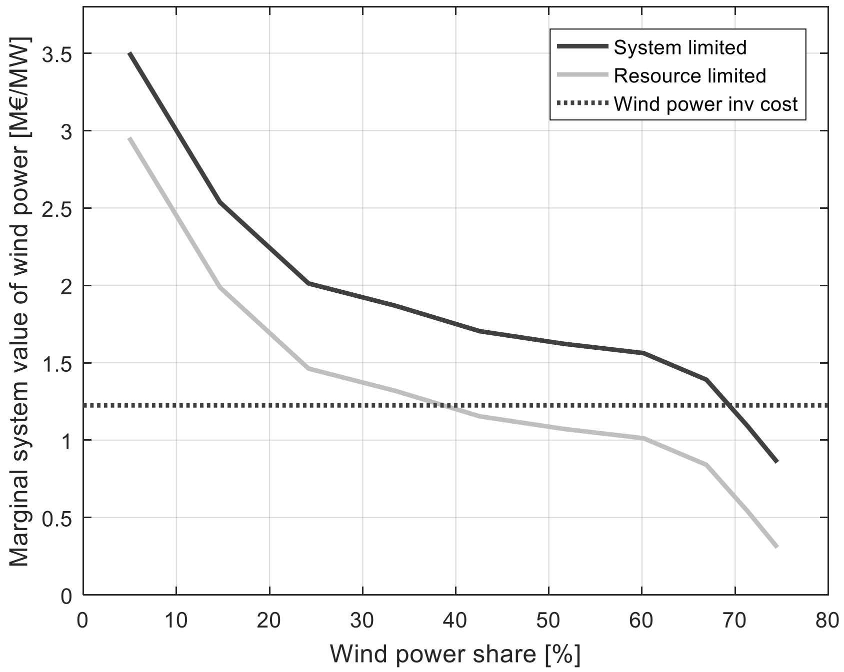

Figure 2: Explanation of the marginal system values of wind power for a resource-limited region and a system-limited region. The marginal system value represents the willingness to pay for additional wind power investments at different levels of wind integration [21]. *The marginal value can remain above the investment cost longer or shorter than is shown in the figure, depending on the system conditions and the availability of variation management.*

4.2 The impact of variation management on system composition

In general, cost-optimal investments in wind and solar power are increased with the addition of one or several VMS to the available technology mix. In resource-limited regions, there is a strong potential to increase the renewable share, whereas in system-limited regions there is instead the possibility to improve utilisation of the already installed VRE capacities or to increase the VRE capacities when expanding the system to support other sectors or regions. The strong connections between solar integration and shifting strategies, such as batteries and household DSM (mentioned in Section 4.1) are described in **Papers I** and **III**. From **Papers I** and **II**, the roles of complementing VMS, such as biogas power or reduced electricity consumption for hydrogen production, in supporting wind power during few but durable periods of low output are clearly beneficial in competition with baseload generation. The roles of absorbing strategies are mainly of interest when it comes to increasing wind power in situations where there are under-utilised good resources, i.e., what we call ‘system-limited regions’. This is mainly seen in cases of opportunistic system expansion, for example, using power-to-heat for district heating (**Paper I**) and expanding the geographical boundaries with transmission (**Paper IV**).

When the model makes an investment, it is always the most economical choice based on boundary constraints and input data. Therefore, the model makes the most of every opportunity. Thus, it is interesting to allow more than one VMS at a time in the model. The downside of each VMS category, i.e., the expensive energy storage capacity of shifting strategies, the high cost of capacity for many complementing strategies, and the un-timely opportunities of many absorbing strategies, can suddenly be bridged by combining strategies from different categories. In **Paper I**, batteries, electric boilers (power-to-heat), hydrogen storage, low-cost biomass (30 €/MWh, reduced from 40 €/MWh), and household DSM (20% of demand delayed for up to 12 hours) were added one-by-one, as well as all together (*Full Flex*). Short-term storage units can shift the load and generation to less-intense net-load events that better suit the complementing and absorbing strategies. Shifting strategies can, for example, reduce the need for expensive electrolyser capacity that is required for industrial electrification. Figure 3 (a) and (b) shows how the capacities of wind power and solar PV are increased to a greater extent by the combination of all these strategies than by the sum of the individual strategies, for the two resource-limited regions. Wind power also benefit from the increase in solar PV, and vice versa, as baseload generation is pushed out of the system, as can be seen in Figure 2. When the conditions for wind or solar generation are very good, i.e., system-limited, VMS can enable wind power to push out solar PV, as shown in Figure 3 (c) and (d) or solar PV to push out wind power (as in the case of large-scale V2G implementation in sunny regions, such as central Spain; **Paper III**).

Biogas, derived from gasified biomass, is the main fuel used for complementing VRE in most of the zero-emission systems presented in **Papers I**–**IV**. However, as bioenergy is expected to be in short supply in the future, the cost and availability of biogenic resources for usage in the electricity sector are highly uncertain. In **Paper II**, the biomass availability was varied within the range of 0%–100% of the electricity demand in terms of primary energy; the resulting electricity mixes are visualised in Figure 4. Along with bio-based generation wind, solar, nuclear, fossil fuel-based generation with CCS, batteries, and hydrogen storage systems were included in the model. At very low levels of biomass availability, it is expensive to maintain the hourly electricity balance for high shares of VRE. At this low level of biomass, nuclear power is favoured to a large degree. However, since the levelised cost of VRE is expected to be (much) lower than the levelised cost of nuclear power, the biomass is utilised so as to provide as much complementing generation as possible to VRE. The optimal utilisation of biomass is then to use it for BECCS, and the leeway in emissions provided by capturing biogenic carbon dioxide is used for flexible electricity generation based on natural gas, until such time as a sufficient amount of bioenergy is available to replace the natural gas with biogas. The BECCS plants by themselves do not provide flexibility, primarily due to the high investment cost. The use of BECCS for achieving net-negative emissions, rather than for allowing the use of fossil fuels, could thereby replace other baseload generation in resource-limited systems, although it would compete with wind power and solar PV in system-limited regions. Therefore, negative-emissions policies imposed on the electricity sector do not result in additional flexibility for VRE integration as a side-effect, and bioenergy use for negative emissions could conflict with the need for bioenergy as a means to ensure flexibility for integration of VRE. In regions with unusually good conditions for VRE, here represented by Ireland, 100% renewable systems (supplemented only by batteries and hydrogen storage) may be the most cost-efficient option, also without any biomass (or any hydropower). In such a case, increased biomass availability competes with the utilisation of wind power.

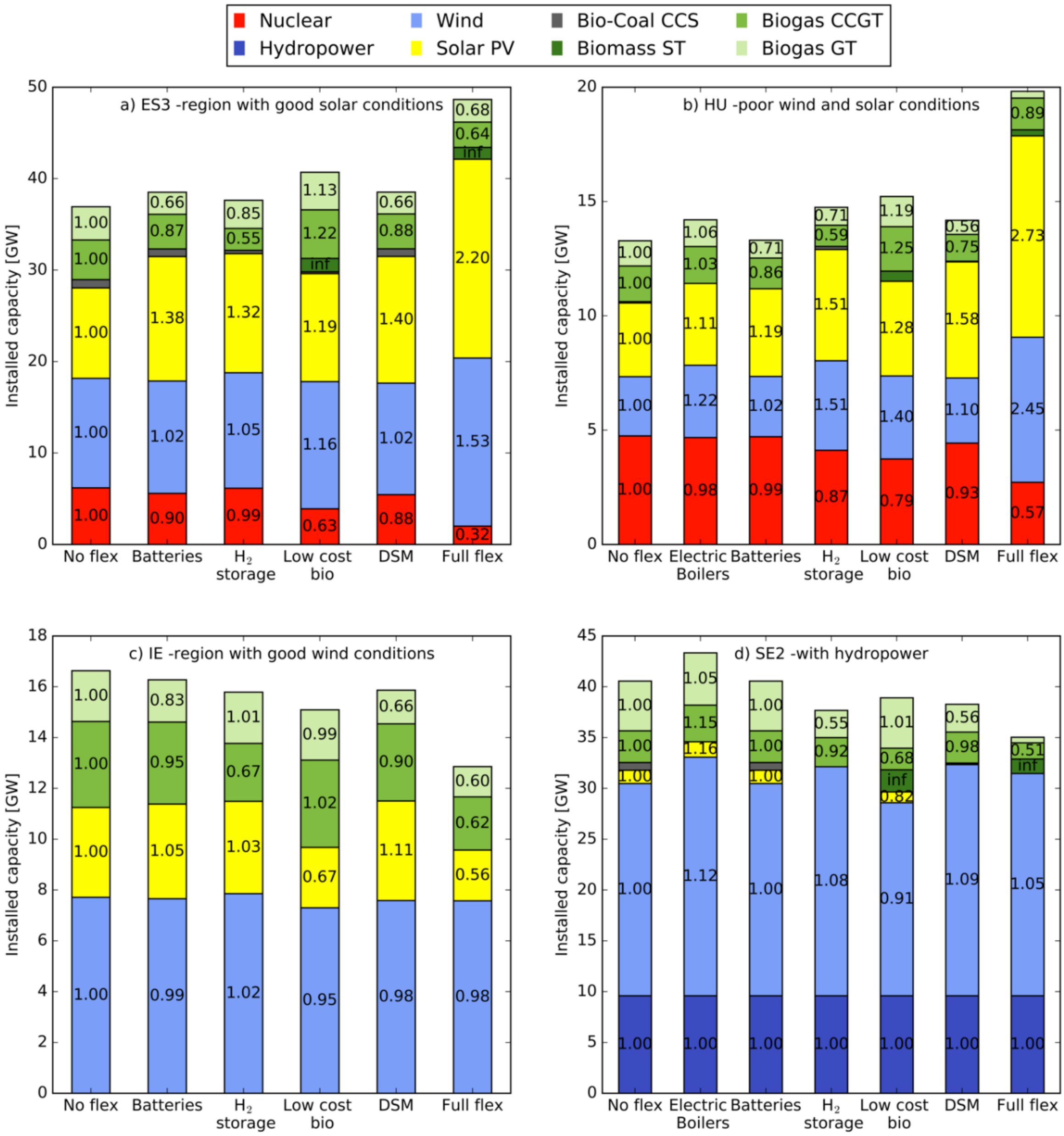

Figure 3: Installed capacities in the VMS scenarios in the four regions. The number in each box represents the share of capacity compared to the No Flex case; thus, capacities that are not present in the No Flex case are denoted as ``inf'' (infinitely). The values for capacities of less than 1 GW are removed to improve readability. The Full Flex case combines all the other VMS. Source: ***Paper I***.

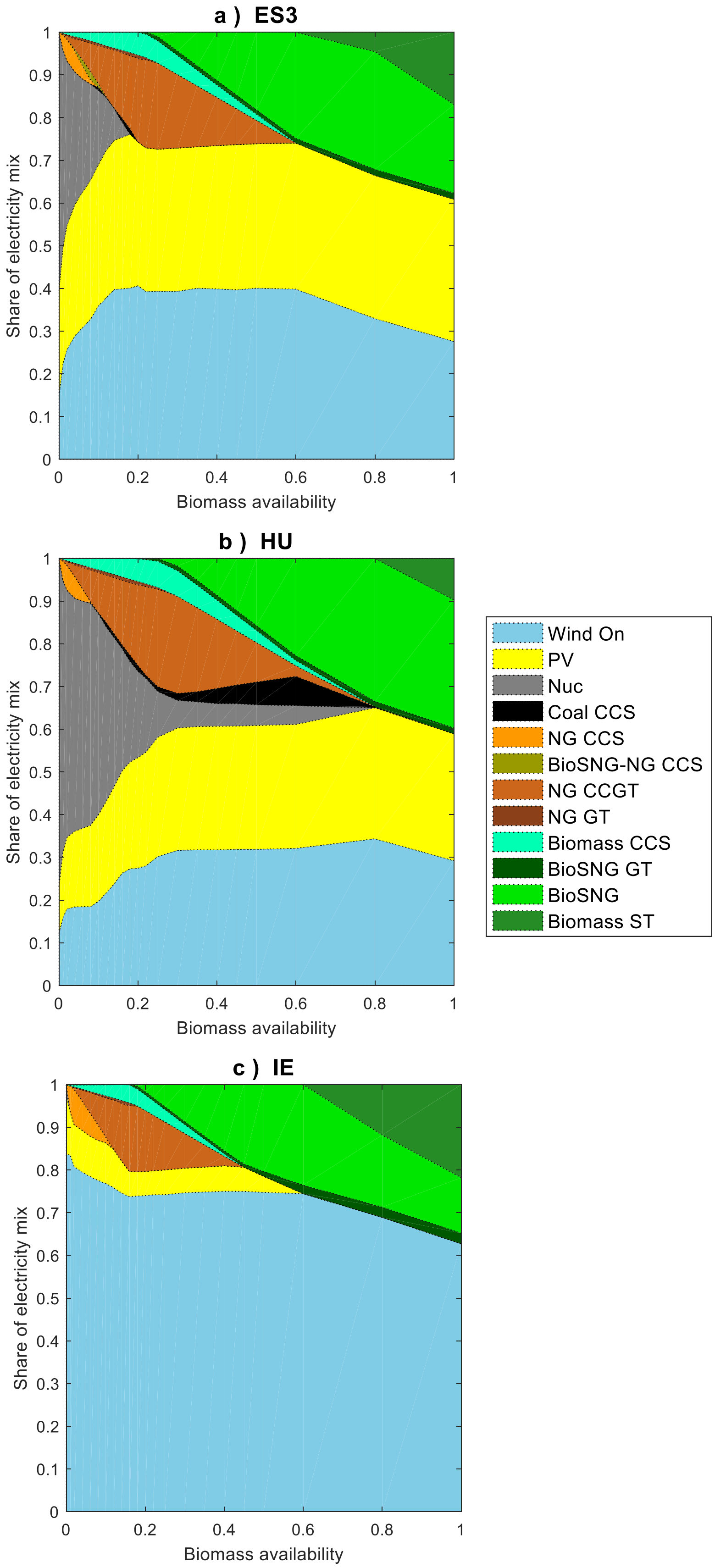

Figure 4: The electricity mixes for different levels of biomass availability for three regions. The term 'biomass availability' refers to the primary energy in the available biomass divided by the total demand for electricity. Source: ***Paper II****.*

4.3 Variation management strategies that provide multiple benefits

Adding dedicated units, such as batteries and gas turbines, to the electricity system may not be the most cost-efficient way to balance supply and demand in the future electricity system. Options for energy storage are built-in or involve a low additional cost when electrifying new sectors, such as cars or industries. The direct reduction of both local and global emissions through fuel switching from fossil petroleum or diesel to (preferably carbon-neutral) electricity is the main driver for electric cars. In electric cars, batteries are the modern fuel tank and the battery size, which determines the range per charging cycle, is dimensioned based on cost, weight and available space, as well as the desire for personal freedom. In **Paper III**, individual cars up-scaled to 60% of today's car fleet are modelled with three different battery sizes and with the opportunity to discharge the batteries back to the grid (V2G – vehicle-to-grid). The cars not only avoid charging during peak hours, but also supply electricity during these peaks by discharging electricity back to the grid. The optimised storage patterns of stationary batteries and 30-kWh car batteries are of similar size, and the trend can be compared in Figure 5 (a) and (c), which shows the states of charge for stationary storage units and for cars with V2G, respectively. The daily charging of the car batteries needs to be more intensive than for stationary batteries in order to satisfy also the driving demand. If larger batteries (85 kWh) become standard, they could also mimic the pattern of long-term hydrogen storage, as shown in Figure 5 (b) and (d). With full-scale smart charging and V2G, stationary batteries become redundant, while the long-term storage systems can only be replaced to a certain extent. Smart charging of electric cars and V2G make it possible to expand generation from VRE already during the transition from the current system, and may thereby promote a faster transition of the electricity system [38].

Electrification is seen as a way to decarbonise not only the transport sector, but also the industry sector, as evaluated in **Paper I**. However, in contrast to electric cars, industries are stationary and can, for some purposes, utilise hydrogen in the processes. This makes industries well-suited to long-term hydrogen storage for the purpose of avoiding peak-load electricity prices. Figure 6 shows how the hydrogen storage is slowly charged, to be utilised during high-net-load events. To balance supply and demand during high-net-load events, hydropower is first utilised to its maximum (i.e., 9.6 GW), followed by shutting down of the electrolysers and discharging of the hydrogen storage units. The modelling results show that the cost of hydrogen storage and added electrolyser capacity can be covered by the lower cost of electricity, as compared to inflexible hydrogen production without storage. Both the industry case and transportation case show how the electricity system can benefit from economically rational behaviours in other sectors.

When assessing the role of trade in **Paper IV**, two regions were paired on the basis of the possibility to invest in transmission for a low or high cost (1 or 3 M€/MW, independent of distance for the sake of simplification). With expensive transmission capacity, the trade is more even over the year, whereas low-cost transmission results in more unidirectional trade. The resulting trade pattern is aggregated over time to envision how the state of charge would have been for a storage option, as shown in Figure 7. All of the cases result in one over-arching cycle (with almost sinusoidal shape), which for some cases ends with a large negative surplus (i.e., region IE is a net-exporting region). The figure illustrates the behaviour of trade as a long-term VMS that does not require a storage capacity over which it has to maintain an energy balance. Trade gives high-wind regions with the opportunity to expand the wind share even further to facilitate net-export. This can induce co-benefits for solar investments, as the importing region gets the opportunity to export electricity back during summertime when European wind power is usually generating less electricity [59].

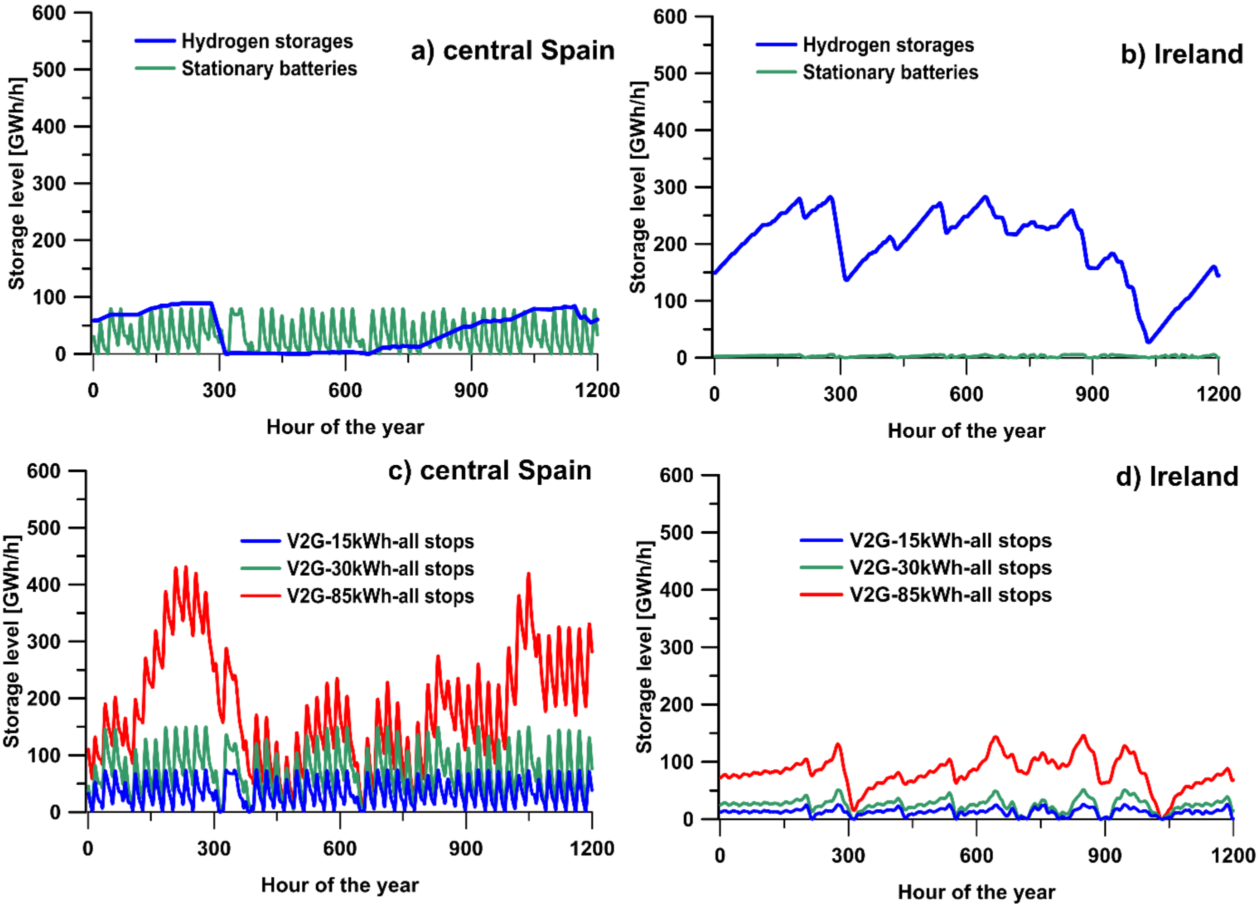

Figure 5: Storage levels of hydrogen and stationary batteries in the case with direct charging of EVs at all stops longer than 1 hour and with a battery capacity of 30 kWh for: (a) central Spain; and (b) Ireland. Also shown are the storage levels of EV batteries in a model run with V2G, assuming charging at all stops longer than 1 hour and battery capacities of 15, 30 and 85 kWh for: (c) central Spain; and (d) Ireland. Source: ***Paper III****.*

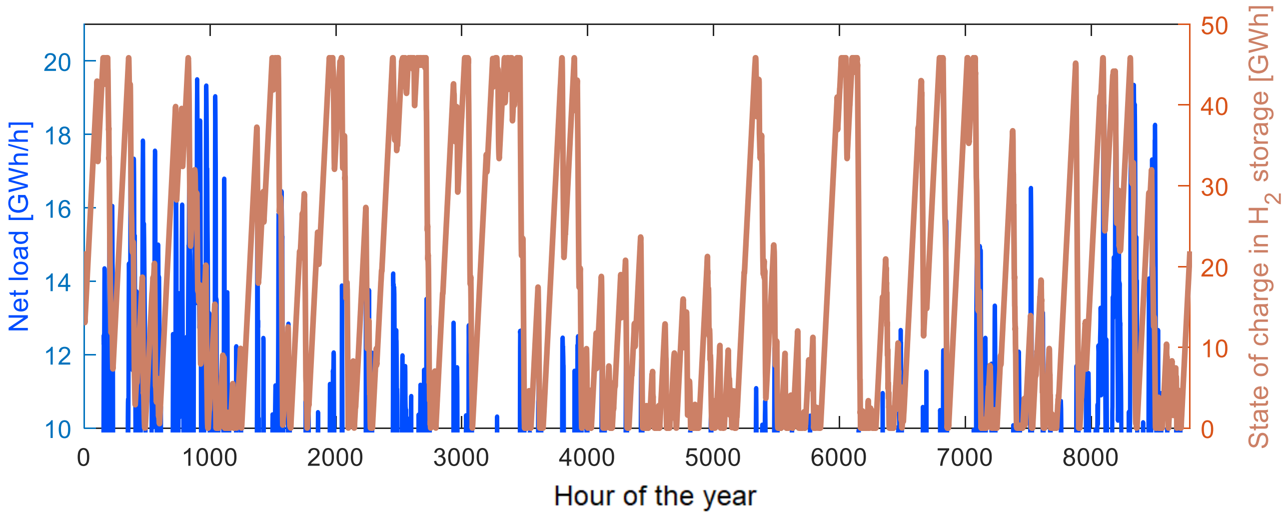

Figure 6: Operation of a hydrogen storage unit in central Sweden and the net load that exceeds 10 GW (broken left vertical axis) in the same region for the year investigated. (In the central Sweden region, there is a hydropower capacity of 9.6 GW, given exogenously.) The hydrogen storage is subject to approximately 20 large cycles over the course of a year. Charging is slow, typically taking around 1 week, whereas discharging is faster, typically requiring 1–2 days, and is highly correlated with net load events exceeding 10 GWh/h. Source: ***Paper I****.*

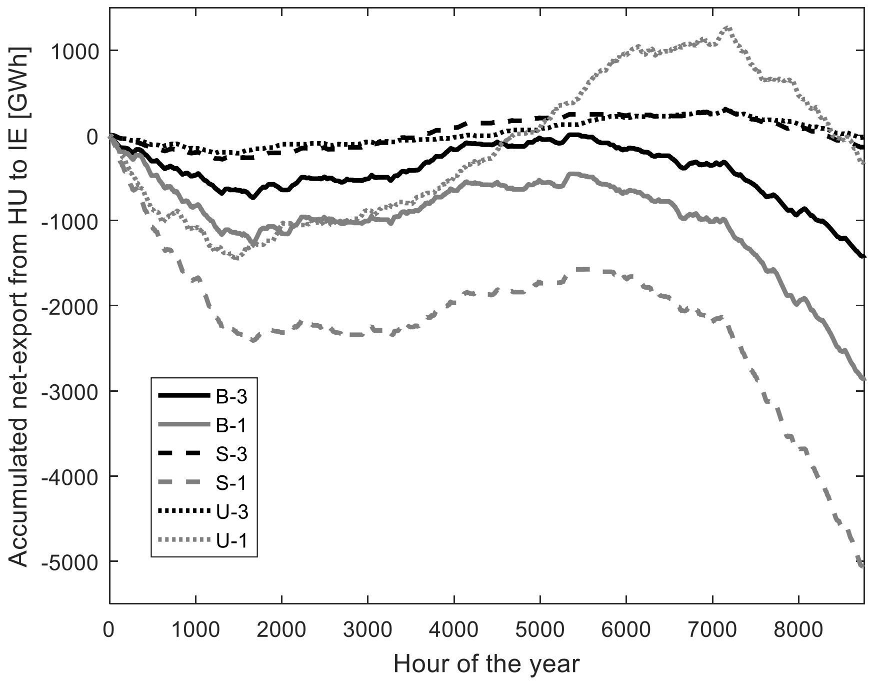

Figure 7: Accumulated trade from the net-importing region Hungary (HU) to the net-exporting region Ireland (IE). A negative end-value indicates that IE has exported more to HU than what was imported. The letters B (base case), S (stable synchronised), and U (unstable synchronised) represent the wind profile cases, while numbers 1 and 3 represent the investment costs of transmission in M€/MW. Source: ***Paper IV****.*

4.4 Value of variation management

According to **Paper I**, VMS reduce the total system costs and the VRE share is increased in most of the cases, as shown in Figure 8. In central Sweden, which has a large fraction of in-built flexibility from hydropower already in the No Flex case, the system cost savings from VMS in the Full Flex case are about 8%. The cost savings are as high as 17% in Ireland, due to the reduced need for investments in generation capacities. The cost savings are mostly derived from hydrogen storage, DSM, and the usage of low-cost biomass, with the latter two VMS being provided for free to the model (i.e., DSM and biomass rebated from 40 to 30 €/MWh_{th}). The use of batteries generates rather large cost savings in central Spain, but only minor savings in the other regions. The electric boilers have a weak impact on the total cost, although they increase the share of VRE in the two systems in which they were examined.

In **Paper III**, the benefit of increasing in a stepwise manner the number of cars that take part in V2G is analysed in relation to the number of participants and the specific region. As shown in Figure 9, the marginal value of V2G participation declines from the initial value, being limited by the annualised investment cost of stationary batteries that are replaced by V2G. As all batteries are replaced, the additional car batteries are used more sporadically for V2G, since longer variations demand longer duration of storage. Nevertheless, some long-term hydrogen storage can be replaced, thereby keeping the value above zero until most of the fleet is part of the V2G strategy. This similarity to stationary batteries, together with strategies for smart charging for the driving demand means that the electric cars have the potential to act as a shifting strategy with some absorbing features. The total system savings compared to direct charging is in the range of 4%–11% for optimised charging and 8%–33% for V2G for the four regions with medium-sized batteries, assuming no cost for the strategies; these savings are as large or larger than the savings derived from combining all the VMS in **Paper I**. The savings obtained in solar-dominated central Spain are about double those made in wind-dominated Ireland and four-times larger than those obtained in Sweden, due to the already existing flexibility from hydropower.

The uncertain supply of bioenergy and how best to utilise it under scarcity is addressed in **Paper II**. The system value biomass relative to biomass availability is shown in Figure 10. A similar overall trend is seen for all the scenarios and regions: a high initial value that drops rapidly until it reaches 0.15–0.25 MWh_{th}/MWh_{demand} (enough to cover about 5%–10% of the electricity demand), after which it declines slowly. In the base cases, the biomass value is in the range of 150–180 €/MWh_{th} at 0.01 MWh_{th}/MWh_{demand}, whereby the supply is not sufficient to cover rare high-net-load peaks. These are followed by an intermediate value of about 30–80 €/MWh_{th} where durable intermediate-net-load events are to be matched. The decline in value is slower without CCS, as more biomass is needed to supply the requirement for complementing generation if biomass cannot be combined with fossil fuels, in a situation where the negative emissions from BECCS match the fossil emissions. The value for biomass stabilises in the range of 20–30 €/MWh_{th}, achieved through competition with investments in wind power and solar PV. A relatively low cost of biomass would support the integration of VRE, whereas too low a cost would result in the opposite and would be a sign of a superfluously large out-take of biomass.

In **Paper IV**, transmission of electricity at different costs is addressed, to capture the value of transmission between the trading regions. Figure 11 shows the relative system cost savings for different costs of transmission. The savings are largest for those cases in which trade enables both resource transfer and geographical smoothing between regions where one region has good wind conditions, illustrated by the black and red solid lines in Figure 11. Resource transfer, together with geographical smoothing reduces the cost by 5%–7% with access to transmission at 3 M€/MW and by 9%–12 % at a transmission cost of 1 M€/MW, where the higher value relates to the cases that connect regions located farther apart (black lines compared to red lines in Figure 11). For comparison, the cost is reduced by only about 1.5% when connecting two low-wind regions (blue/teal lines in Figure 11). By removing the differences in wind profile (dashed and dotted lines in Figure 11), the system benefit of resource transfer alone is 0.2%–2% of the total system cost for a transmission cost of 3 M€/MW, indicating that a large part of the value of trade is attributable to geographical smoothing. At a transmission cost of 1 M€/MW, however, resource transfer can reduce the total system cost by 3%–8%. Thus, resource transfer by itself has a significant impact on the total system cost at a low cost for transmission. When the trading regions have synchronised wind profiles, sharing the more stable profile from the region with good wind conditions gives 5%–9% lower total system cost than if the unstable profile from the low-wind region is used. This indicates that there is a smoothing element also to resource transfer.

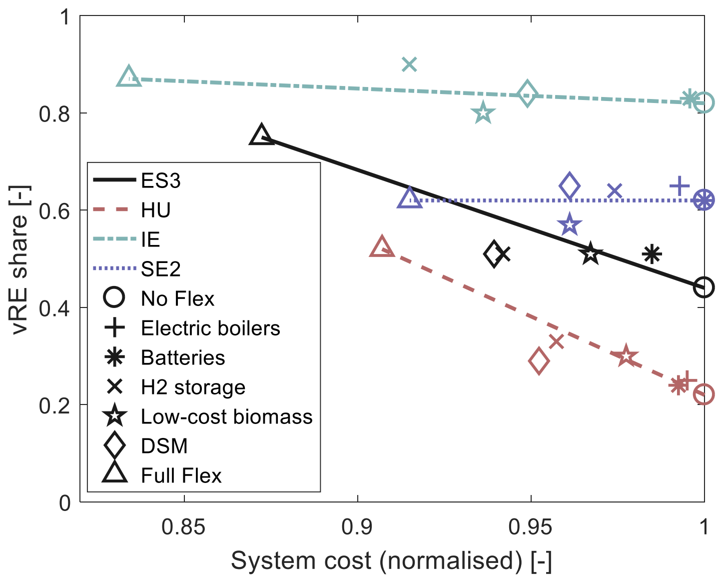

*Figure 8: The VRE share and system costs (normalised to the cost for the No Flex case) for the different VMS cases and different regions. The lines connect the No Flex and the Full Flex cases. Note the broken horizontal axis. Source: **Paper I**.*

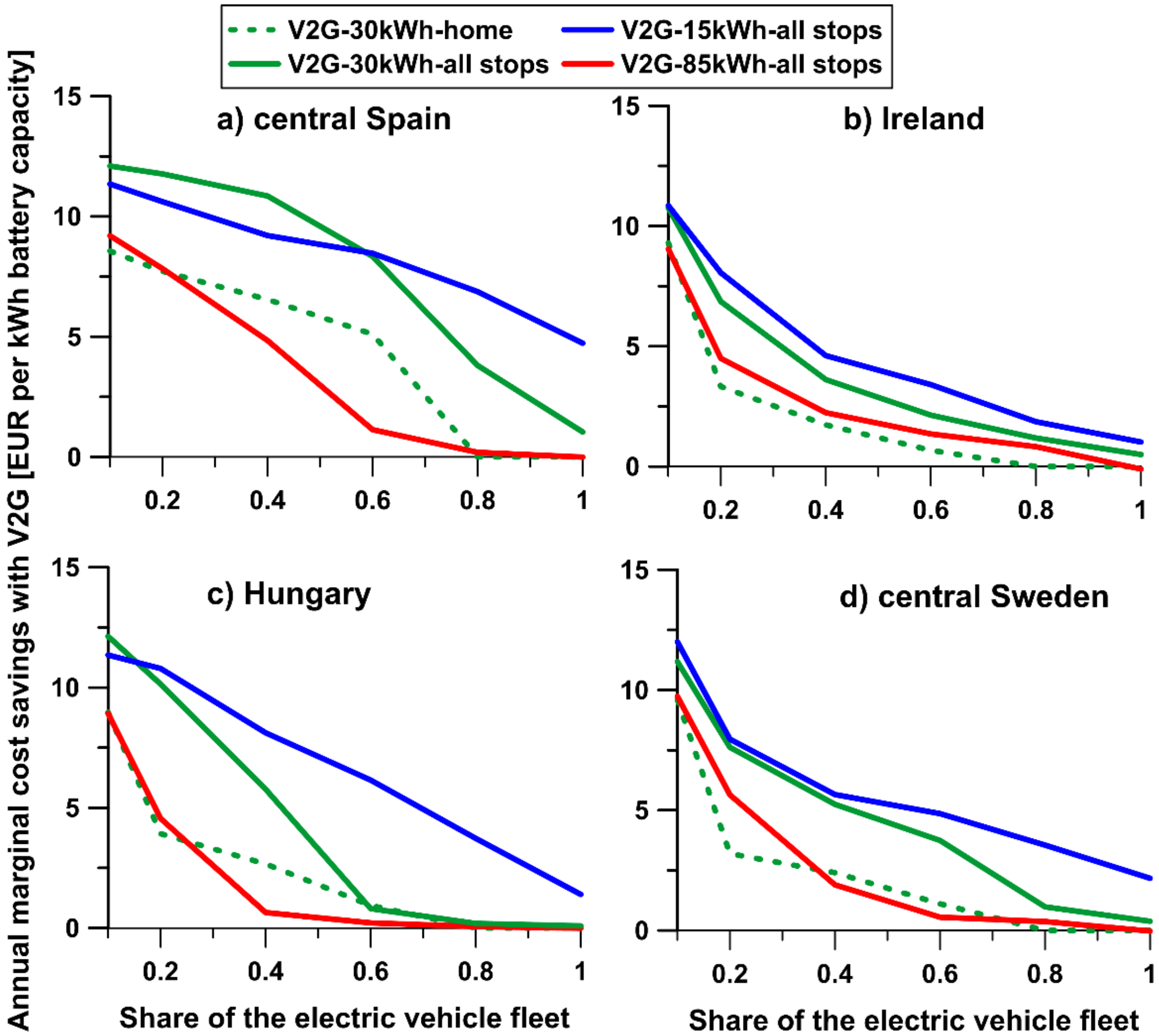

Figure 9: Annual marginal cost savings with V2G (in EUR) per kWh of battery capacity in relation to the share of the electric vehicle fleet that is participating in V2G, for different battery sizes (15, 30 and 85 kWh), regions and charging infrastructure (i.e., charging at all stops or at home location). Source: ***Paper III****.*

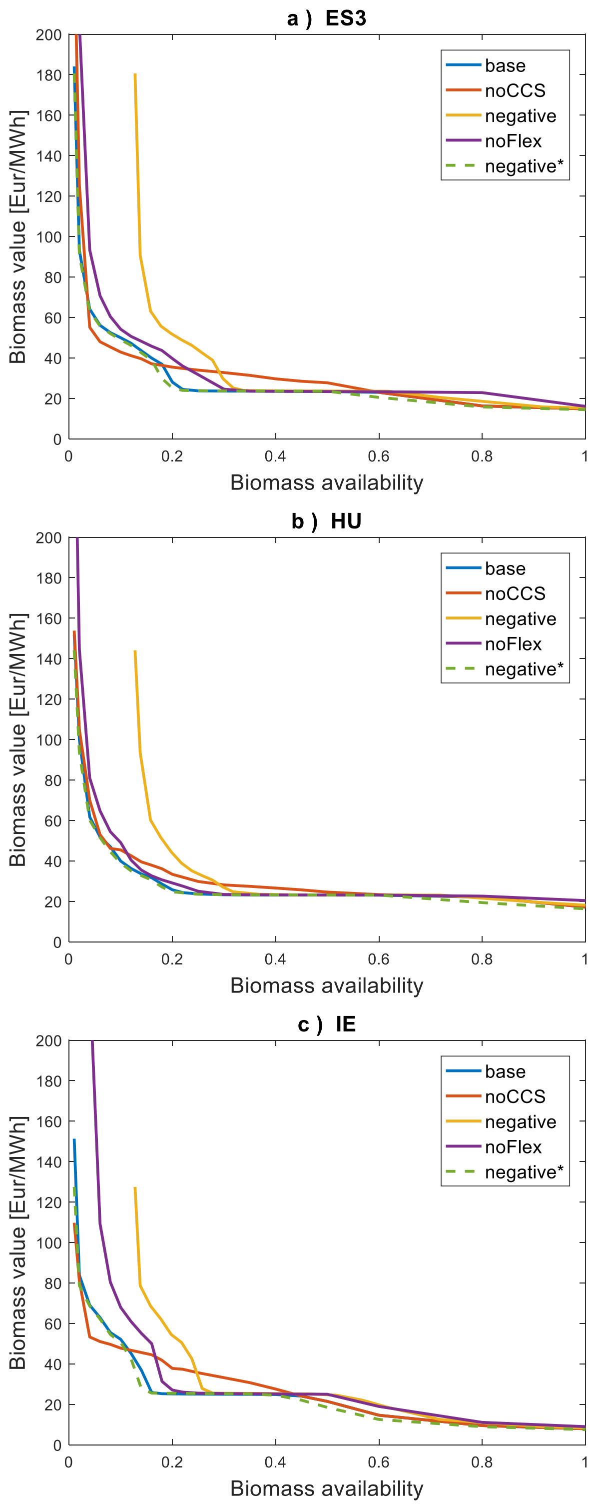

Figure 10: Biomass values for different biomass availability levels for the four scenarios. In the case "noCCS", CCS is not allowed; in the case "negative", there is a need for 10% negative emissions; in the case "noFlex", energy storages are not allowed. The green, dashed line represents the case "negative", where the biomass needed for negative emissions is excluded from the availability, i.e., the (yellow) curve is shifted to start at zero biomass availability. Source:* ***Paper II****.*

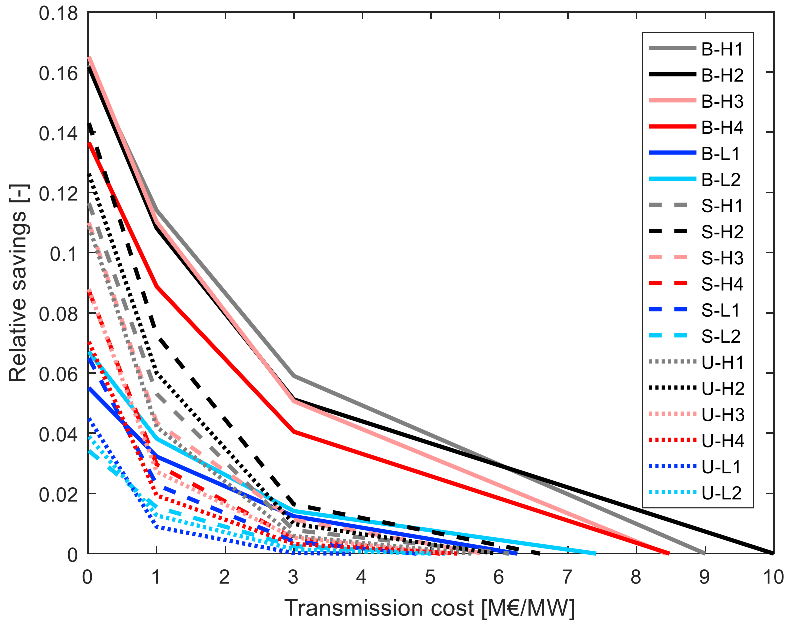

Figure 11: The system cost savings relative to the cost without any trade. The solid, dashed, and dotted lines represent the different wind profile cases. The transmission cost at which the value starts is given from the marginal value of transmission for the runs with 10 M€/MW. The letters B (base case), S (stable synchronised), and U (unstable synchronised) represent the wind profile cases. H1-H4 and L1-L4 represent the trading region pairs, where H means that one of the two regions has good wind conditions and L that both regions have poor wind conditions. Source: ***Paper IV****.*

5 Discussion, conclusions and future work

5.1 Discussion

There are multiple dimensions and levels of detail in energy systems modelling. The level of detail is determined by the geographical scope, temporal scope (both for the investment horizon and number of time-steps per year), number of technologies, and the boundaries to the rest of the energy system. In all the work presented here, the modellers have had to choose the scope in order for the model to be feasible. In **Papers I–IV**, there is a high level of detail with regards to the number of time-steps per year, as well the number of technologies represented, including the technologies used for variation management. There are lower levels of detail with regards to the other dimensions, with parts of other sectors or an extra region added one-by-one to address specific questions. If all the VMS were included in the most-flexible settings, i.e., with both sectorial and geographical coupling, the individual effects of the VMS options would be reduced. The stepwise additions of VMS in this work, however, provide information that increases our understanding of the impacts of VMS on both investments in and operations of the electricity system.

If VRE integration is limited by land-use and NIMBY (not in my backyard) attitudes, there will be a competition for this clean energy that will push for energy efficiency measures. Energy systems with limited availability of VRE will also need fewer VMS. However, if wind power is limited by acceptance but not solar PV, due to the lower visual and aural impacts of the latter, there may instead be a greater need for variation management, and in particular shifting strategies.

Modelling sectors with more options than just 0% or 100% electrification could provide insights into how to utilise resources in a better way when all sectors compete for the low-hanging energy carriers. On the one hand, this type of model could also provide a better ordering of those VMS that in competition could take on specific roles. On the other hand, development of a wider mix of VMS than the obvious winners from an economic perspective may be of importance when some barriers to large-scale expansion of these low-cost VMS are found to be impossible to overcome.

5.2 Conclusions

Variation management can increase the amount of cost-efficient variable renewable electricity that can be integrated into the system while reducing the cost to meet the demand for electricity in carbon-neutral electricity systems. The choice of VMS for the integration of VRE is highly dependent upon the system context. To capture these contexts, the concepts of system-limited and resource-limited regions are defined. System-limited regions benefit from absorbing VMS to increase the utilisation of wind power and decrease the need for supplementary electricity generation. In resource-limited regions, on the other hand, complementing technologies are needed to enhance wind power production and to out-compete baseload generation technologies. Shifting strategies are mainly suited to the diurnal variations of solar PV. However, combinations of the categories of strategies, as well as combinations of wind and solar are shown to benefit further the employment of VRE, since expensive or limited storage units or capacities can be better utilised with support from other strategies. This knowledge is based on the knowledge acquired through the studies described in the appended Papers, where we show that:

- Most VMS increase the potential for integration of wind power and solar PV and reduce the system cost. VMS from different categories can synergise to suppress investments in power and storage capacities to manage variability. A combination of VMS can have a greater effect on VRE integration than the sum of the individual strategies.
- The need for complementing VMS for dealing with some durable high- and intermediate-net-load events is evident when the goal is to reach high shares of VRE in a cost-efficient manner in resource-limited systems. When the supply of biomass is poor, the value of flexible generation is high, and a small amount of bioenergy can maximise its flexibility in a carbon-neutral system through CCS technologies, making room for flexible, natural gas-based generation. Biomass-based generation can compete with VRE integration when there is a strong supply of biomass or when BECCS is needed for net-negative emissions in the electricity sector in system-limited regions. This highlights the importance of the choice of system boundary for allocating negative emissions to where they are most appropriate, as well as the need to identify and activate complementing strategies from sources other than those that rely on biomass.
- The integration of electric vehicles through smart charging and V2G could provide a large part of the flexibility needed for large-scale integration of VRE. Utilising both car batteries and the flexibility from household DSM can reduce the need for stationary batteries while supporting the integration of solar PV. Optimised charging of electric cars, together with V2G has a greater impact on system cost reduction than a combination of several other VMS.
- Transmission allows wind power to support itself by exploiting geographical differences in wind speeds. Geographical smoothing can be achieved already with small transmission capacities, whereas a large transmission capacity handle seasonal variations from PV and wind power to a larger degree as well as transfer large wind resources and expand the wind power capacities in system-limited regions so that they can export to resource-limited regions.

This techno-economic description of how variation management can be adapted to different purposes underscores the need for policymakers to bear in mind that the needs for their system are dependent upon the context and surrounding resources. It also emphasises the importance of combining different technologies and strategies and using them where they are most appropriate, rather than deploying a single strategy for everything.

5.3 Future work

By utilising the flexibilities that can be found in the electricity system of today and in the future, sufficient flexibility can be found to balance in a cost-efficient way very high levels of VRE. Nonetheless, transitioning from being techno-economically feasible to working in reality is not simple. Therefore, to actualise a rapid transition to systems with high levels of VRE, it is necessary to implement the VMS as well as break other barriers. In my opinion, NIMBY attitudes represent a major obstacle to efforts to promote high levels of acceptance for wind power, as well as other carbon-neutral electricity sources and VMS.

Even if the electricity is supplied from carbon-neutral sources, there is no guarantee that it also will be sustainable. Limitations linked to the availability of wind areas, metals, and bioenergy are not currently regarded as showstoppers. However, if the system keeps on growing and no efficiency measures are introduced, such limitations may become debilitating. When looking at current and future energy demands, not only flexibility measures, but also efficiency measures are interesting to study.

Improved modelling of VRE integration in full energy system models could improve understanding of: where best to allocate limited resources such as biomass; limited electricity availability as a consequence of poor acceptance of VRE; and the value of units that generate negative emissions. The ongoing efforts to create new models that can capture everything or to identify improvements in connections between models at different system levels may be facilitated by the steps taken in this thesis towards understanding variability and the potential of flexibility measures.

References

[1] United Nations, “The Paris Agreement,” 2015.

[2] S. Fuss *et al.*, “Betting on negative emissions,” *Nat. Clim. Chang.*, vol. 4, no. 10, pp. 850–853, 2014.

[3] European Commission, “A Clean Planet for all - A European long-term strategic vision for a prosperous , modern , competitive and climate neutral economy,” 2018.

[4] B. Kroposki, “Integrating high levels of variable renewable energy into electric power systems,” *J. Mod. Power Syst. Clean Energy*, vol. 5, no. 6, pp. 831–837, 2017.

[5] F. Creutzig *et al.*, “Bioenergy and climate change mitigation: An assessment,” *GCB Bioenergy*, vol. 7, no. 5, pp. 916–944, 2015.

[6] R. Slade, A. Bauen, and R. Gross, “Global bioenergy resources,” *Nat. Clim. Chang.*, vol. 4, no. 2, pp. 99–105, 2014.

[7] K. Hedegaard, H. Ravn, N. Juul, and P. Meibom, “Effects of electric vehicles on power systems in Northern Europe,” *Energy*, vol. 48, no. 1, pp. 356–368, 2012.

[8] G. Giebel, N. G. Mortensen, and G. Czisch, “Effects of large-scale distribution of wind energy in and around Europe,” *Energy Technol. Post Kyoto targets Mediu. term. Proc.*, pp. 115–124, 2003.

[9] H. Lund *et al.*, “Energy Storage and Smart Energy Systems,” *Appl. Energy*, vol. (Pending), pp. 3–14, 2016.

[10] L. Göransson and F. Johnsson, “A comparison of variation management strategies for wind power integration in different electricity system contexts,” *Wind Energy*, vol. 21, no. 10, pp. 837–854, 2018.

[11] L. Göransson, V. Johansson, M. Lehtveer, and F. Johnsson, “Från timmar till årtionden -hur påverkar variationr i last och produktion sammansättningen av Sveriges och Europas framtida elsystem?,” 2018.

[12] S. Stoft, *Power System Economics*. JOHN WILEY & SONS, INC, 2002.

[13] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, “Review of energy system flexibility measures to enable high levels of variable renewable electricity,” *Renew. Sustain. Energy Rev.*, vol. 45, pp. 785–807, 2015.

[14] H.-K. Ringkjøb, P. M. Haugan, and I. M. Solbrekke, “A review of modelling tools for energy and electricity systems with large shares of variable renewables,” *Renew. Sustain. Energy Rev.*, vol. 96, pp. 440–459, Nov. 2018.

[15] D. P. Schlachtberger, S. Becker, S. Schramm, and M. Greiner, “Backup flexibility classes in emerging large-scale renewable electricity systems,” *Energy Convers. Manag.*, vol. 125, pp. 336–346, Oct. 2016.

[16] L. Göransson, J. Goop, M. Odenberger, and F. Johnsson, “Impact of thermal plant cycling on the cost-optimal composition of a regional electricity generation system,” *Appl. Energy*, vol. 197, pp. 230–240, 2017.

[17] S. Ó. Garðarsdóttir, L. Göransson, F. Normann, and F. Johnsson, “The value of flexible thermal generation- from CCS plants.”

[18] L. Hirth, “The benefits of flexibility: The value of wind energy with hydropower,” *Appl. Energy*, vol. 181, pp. 210–223, 2016.

[19] H. Klinge Jacobsen and S. T. Schröder, “Curtailment of renewable generation: Economic optimality and incentives,” *Energy Policy*, vol. 49, pp. 663–675, Oct. 2012.

[20] L. Hirth and S. Müller, “System-friendly wind power. How advanced wind turbine design can increase the economic value of electricity generated through wind power,” *Energy Econ.*, vol. 56, 2016.

[21] V. Johansson *et al.*, “Value of wind power – Implications from specific power,” *Energy*, vol. 126, pp. 352–360, 2017.

[22] E. Rinne, H. Holttinen, J. Kiviluoma, and S. Rissanen, “Effects of turbine technology and land use on wind power resource potential,” *Nat. Energy*, vol. 3, no. 6, pp. 494–500, 2018.

[23] W. Cole, B. Frew, P. Gagnon, A. Reimers, J. Zuboy, and R. Margolis, “Envisioning a low-cost solar future: Exploring the potential impact of Achieving the SunShot 2030 targets for photovoltaics,” *Energy*, vol. 155, pp. 690–704, Jul. 2018.

[24] L. Reichenberg, F. Hedenus, M. Odenberger, and F. Johnsson, “The marginal system LCOE of variable renewables – Evaluating high penetration levels of wind and solar in Europe,” *Energy*, vol. 152, pp. 914–924, Jun. 2018.

[25] D. P. Schlachtberger, T. Brown, S. Schramm, and M. Greiner, “The benefits of cooperation in a highly renewable European electricity network,” *Energy*, vol. 134, pp. 469–481, Sep. 2017.

[26] J. Olauson and M. Bergkvist, “Correlation between wind power generation in the European countries,” *Energy*, vol. 114, pp. 663–670, 2016.

[27] L. Göransson, J. Goop, T. Unger, M. Odenberger, and F. Johnsson, “Linkages between demand-side management and congestion in the European electricity transmission system,” *Energy*, vol. 69, pp. 860–872, May 2014.

[28] P. Meibom, J. Kiviluoma, R. Barth, H. Brand, C. Weber, and H. V. Larsen, “Value of electric heat boilers and heat pumps for wind power integration,” *Wind Energy*, vol. 10, no. 4, pp. 321–337, 2007.

[29] P. D. Lund, J. Mikkola, and J. Ypyä, “Smart energy system design for large clean power schemes in urban areas,” *J. Clean. Prod.*, vol. 103, pp. 437–445, 2015.

[30] P. Holmér, J. Ullmark, L. Göransson, V. Walter, and F. Johnsson, “Impacts of thermal energy storage on the management of variable demand and production in electricity and district heating systems: a Swedish case study,” *Int. J. Sustain. Energy*, vol. 0, no. 0, pp. 1–19, 2020.

[31] P. Hou, P. Enevoldsen, J. Eichman, W. Hu, M. Z. Jacobson, and Z. Chen, “Optimizing investments in coupled offshore wind -electrolytic hydrogen storage systems in Denmark,” *J. Power Sources*, vol. 359, pp. 186–197, Aug. 2017.

[32] J. Wohland, D. Witthaut, and C. F. Schleussner, “Negative Emission Potential of Direct

Air Capture Powered by Renewable Excess Electricity in Europe," *Earth's Futur.*, vol. 6, no. 10, pp. 1380–1384, 2018.

[33] J. Kiviluoma and P. Meibom, "Methodology for modelling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles," *Energy*, vol. 36, no. 3, pp. 1758–1767, Mar. 2011.

[34] M. Taljegard, L. Göransson, M. Odenberger, and F. Johnsson, "Impacts of electric vehicles on the electricity generation portfolio – A Scandinavian-German case study," *Appl. Energy*, vol. 235, pp. 1637–1650, Feb. 2019.

[35] B. V. Mathiesen and H. Lund, "Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources," *IET Renew. Power Gener.*, vol. 3, no. 2, p. 190, 2009.

[36] J. Kiviluoma, E. Rinne, and N. Helistö, "Comparison of flexibility options to improve the value of variable power generation," *Int. J. Sustain. Energy*, vol. 6451, no. October, pp. 1–21, 2017.

[37] T. Brown, D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner, "Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system," *Energy*, vol. 160, pp. 720–739, Oct. 2018.

[38] L. Göransson, M. Lehtveer, E. Nyholm, M. Taljegard, and V. Walter, "The benefit of collaboration in the North European electricity system transition—System and sector perspectives," *Energies*, vol. 12, no. 24, 2019.

[39] International Energy Agency, "World Energy Outlook 2016," Paris, France, 2016.

[40] G. Jordan and S. Venkataraman, "Analysis of Cycling Costs in Western Wind and Solar Integration Study Analysis of Cycling Costs in Western Wind and Solar Integration Study," Schenectady, New York, 2012.

[41] J. Persson *et al.*, "Additional Costs for Load- following Nuclear Power Plants," 2012.

[42] M. M. Rienecker *et al.*, "MERRA: NASA's modern-era retrospective analysis for research and applications," *J. Clim.*, vol. 24, no. 14, pp. 3624–3648, 2011.

[43] D. P. Dee *et al.*, "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system," *Q. J. R. Meteorol. Soc.*, vol. 137, no. 656, pp. 553–597, 2011.

[44] J. Olauson and M. Bergkvist, "Modelling the Swedish wind power production using MERRA reanalysis data," *Renew. Energy*, vol. 76, pp. 717–725, 2015.

[45] K. Nilsson and T. Unger, "Bedömning av en europeisk vindkraftpotential med GIS-analys," Mölndal, Sweden, 2014.

[46] Z. Norwood, E. Nyholm, T. Otanicar, and F. Johnsson, "A geospatial comparison of distributed solar heat and power in europe and the US," *PLoS One*, vol. 9, no. 12, pp. 1–31, 2014.

[47] Svensk Energi, "Elåret 2013," 2014.

[48] Svenska kraftnät, "Statistik per elområde och timme 2014," 2015. .

[49] C. Mone, M. Hand, M. Bolinger, J. Rand, D. Heimiller, and J. Ho, "2015 Cost of Wind Energy Review," Golden, Colorado, 2017.

[50] Energistyrelsen, *Technology data for energy plants*, no. August. 2012.

[51] ENTSO-E, “Hourly load values for a specific country for a specific month (in MW),” 2017. [Online]. Available: https://www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month. [Accessed: 27-Sep-2017].

[52] A. Zerrahn and W. P. Schill, “On the representation of demand-side management in power system models,” *Energy*, vol. 84, pp. 840–845, 2015.

[53] Euroheat, “Country by country 2013 - statistics overview,” 2013. [Online]. Available: http://www.euroheat.org/wp-content/uploads/2016/03/2013-Country-by-country-Statistics-Overview.pdf.

[54] J. Holm and J. Ottosson, “The future development of district heating in Gothenburg,” Gothenburg, Sweden, 2016.

[55] S. Nojavan and H. allah Aalami, “Stochastic energy procurement of large electricity consumer considering photovoltaic, wind-turbine, micro-turbines, energy storage system in the presence of demand response program,” *Energy Convers. Manag.*, vol. 103, pp. 1008–1018, Oct. 2015.

[56] S. Karlsson and L.-H. Kullingsjö, “GPS measurement of Swedish car movements for assessment of possible electrification,” *World Electr. Veh. J.*, vol. 6, pp. 955–968, 2013.

[57] H. Thunman, A. Larsson, and M. Hedenskog, “Commissioning of the GoBiGas 20 MW biomethane plant,” in *The international conference on thermochemical conversion science*, 2015.

[58] A. Alamia, S. Ó. Garðarsdóttir, A. Larsson, F. Normann, and H. Thunman, “Efficiency Comparison of Large-Scale Standalone , Centralized , and Distributed Thermochemical Biorefineries,” *Energy Technol.*, vol. 5, no. 8, pp. 1435–1448, 2017.

[59] S. C. Pryor, R. J. Barthelmie, and J. T. Schoof, “Inter-annual variability of wind indices across Europe,” *Wind Energy*, vol. 9, no. 1–2, pp. 27–38, 2006.